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PROBABILITY OF SIMULTANEOUS MULTIPLE LEAKAGES AT SECTIONS OF WATER NETWORKS IN THE PROCESS OF LOCALIZATION OF HIDDEN WATER LEAKS

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Hidden leaks from water supply networks account for 50 % to 90 % of total leakage losses. The presence of two or more simultaneous leaks in a section of the water supply network significantly reduces the accuracy of locating hidden leaks. The method of independent Poisson events and the hypothesis of stationarity, absence of consequences, and ordinariness of leaks are used for the probabilistic description of the problem of multi-leakage in water supply networks. The analytical dependence of the probability of multiple leakages on the specific annual emergency rate of the site, its length and the duration of the localization and repair period is obtained. A generalized semi-empirical equation was obtained for estimating the maximum permissible duration of the localization and repair period depending on the annual emergency rate of the site for a given multi-leakage probability.

Key words: hidden leaks, localization and repair period, multi-leakage probability, simultaneity of leaks, specific annual emergency rate, Poisson distribution.

Introduction

Relative water losses in water supply systems worldwide are estimated at an average of 30 % of the water raised (Duan, 2020). Across the largest cities, this proportion varies from 3 % in Tokyo and Amsterdam and 4 % in Berlin, 13 % in London and 15 % in Los Angeles to 54 % in Alexandria and 58 % in Manila (Duan, 2020; Liemberger & Wyatt, 2019) (Fig. 1). The average share of water losses due to leakages in water supply networks in Poland is about 18 % (Rak & Sypień, 2013). Water losses in the largest cities of Ukraine are estimated at an average of 33.7 %, in particular, 30 % in Kyiv, and 46 % of the System input in Lviv (Natsionalna Dopovid, 2021).

Today, a number of methods are known for hidden leaks localization at water supply networks, including the acoustic method, the correlation method, the gas method, the ground-penetrating radar method, and SCADA systems (Puust, 2010; Chan & Zhong, 2018; Bakhtawar & Zayed, 2021). These methods can be conditionally divided into remote methods, intended for preliminary, approximate determination of the coordinates of the leak, and field methods, which allow finding the leak location on the terrain as accurately as possible. The main problem of field methods is the large specific time spent on leak detection, which leads to both significant volumes of water loss and significant costs for leak detection itself (Lah et al., 2018; Water Efficiency for Water Suppliers, 2021).

Remote methods of locating leaks in water supply networks make it possible to create centralized monitoring schemes even for large networks (SIWA Leak Control, 2015). The most effective remote methods today are complex systems that carry out continuous remote monitoring of water networks, including integrated measurements of pressure, flow and noise accompanying the flow of water in pipes, using the latest advances in IT technologies, in particular GIS, GPS, GSM, as well as cloud software (Kwietniewski et al., 2022).

On the other hand, the standard errors of remote methods in many cases still do not allow to snap the location of hidden leaks with an accuracy sufficient for the immediate start of repair and restoration works (Remeshevska et al., 2021; Zamikhovskyi & Shtaier, 2013). Taking this into account, the most effective today should be combined methods, which involve the use of remote methods for the approximate localization of the largest leaks at the first stage, and field methods for the exact search of a hidden leak in the vicinity of the approximate location at the second stage.

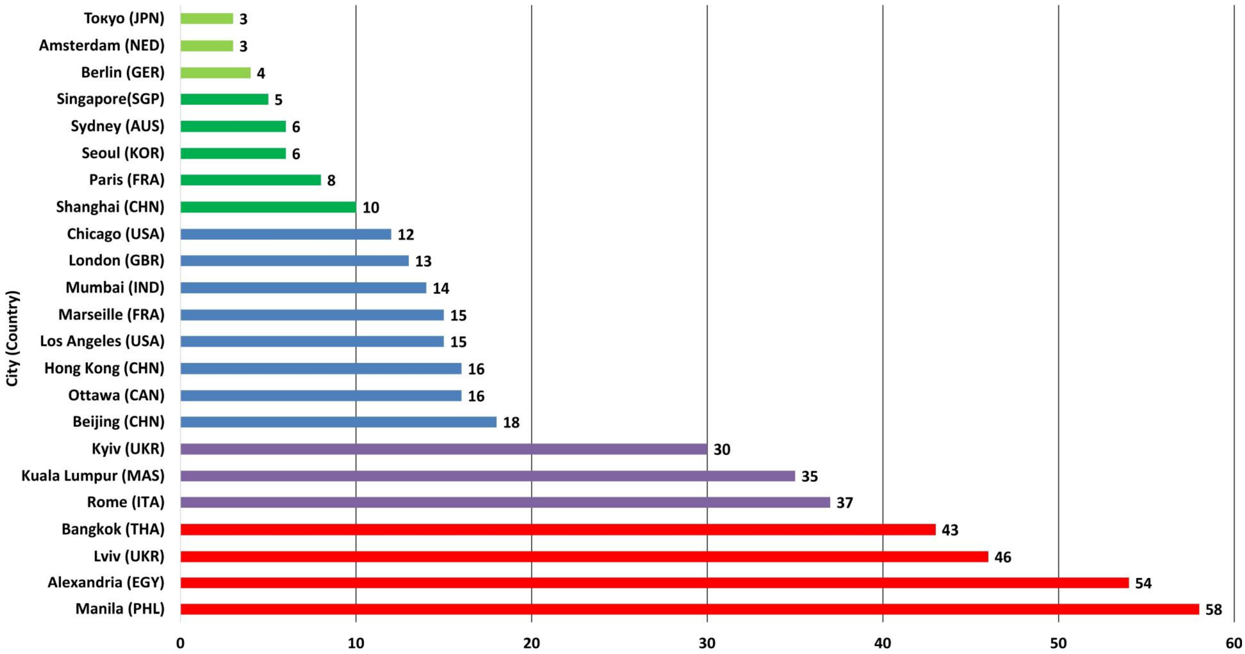


Fig. 1. The share of total water losses (%) in the centralized water supply systems of different cities of the world (Duan, 2020; Liemberger, Wyatt, 2019; National report, 2021)

An important factor affecting the reliability and accuracy of remote methods is the problem of simultaneous multiple leakage of the control section of the network (Anfinsen & Aamo, 2022; Nugroho, 2021). Hydraulic methods of preliminary detection of leaks usually provide sufficient for practice accuracy of the leak location in the case of presence of only one leak in the control section (Babbitt, 1920; Mohammed et al., 2021). The appearance and development of a second leak or more leaks is a major problem for the operation of hydraulic and acoustic methods algorithms (Elandalibe et al., 2015; Jin & Zhou, 2014; Negm, 2023). Thus, a negative feedback loop arises, which consists in complicating the localization of leaks in emergency networks with a high linear density of such leaks along the length of the network, and precisely for such networks the localization task is the most important from a technical and economic point of view.

The purpose of the article is analytical and probabilistic modelling of the problem of simultaneous multiple leakages of sections of water supply networks and testing of the developed models for typical cases of water supply networks in Ukraine and Lviv.

Research materials and methods

Emergency water supply networks in Ukraine and Lviv

The Water Strategy of Ukraine for the period until 2050 states the current “unsatisfactory technical condition, depreciation and insufficient branching of centralized water supply systems”, as well as the presence of significant losses of water resources in centralized water supply systems due to the leakage of networks and the unreliability of shut-off and regulating valves (Vodna Stratehiia Ukrainy, 2022). This regulation sets an ambitious goal of reducing the specific emergency rate of centralized water supply networks by 3 % every year, taking 3.1 $km^{-1}yr^{-1}$ as the initial indicator. Applying the principle of compound interest, this corresponds to the yield on the indicator 2.0 $km^{-1}yr^{-1}$ in 2037, and on the specific emergency rate 1.32 $km^{-1}yr^{-1}$ in 2050.

In general, water supply networks in Ukraine as of 2023 are in a challenging technical condition. In 2020, the total length of water supply networks, according to official data (Natsionalna Dopovid, 2021), was 121.921 km, including 46.602 km or 38.2 % of dilapidated and emergency pipelines, and only 991 km of networks or 2.1 % of the need were replaced during the year 2020. This study also refers to statistical materials on the specific emergency rate of water supply networks in different regions of Ukraine, presented in the National reports on the quality of drinking water and the state of drinking water supply in Ukraine for the years 2007−2020. The analysis of the problem of multi-emergency in the water supply network of Lviv was performed on the basis of the statistical report of LCCE "Lvivvodokanal" for 2020, according to which the water supply network of Lviv has a total length of 2.270 km, of which 67 % of pipelines have an operational life of 35 years and above. In the structure of materials of water pipes, steel (49 %) and cast iron (41 %) pipes prevail, while newer sections made from plastic materials account for about 8 % of the total network length; the remaining 2 % are reinforced concrete pipes. In 2020, 3,202 accidents were eliminated on the Lviv water supply network, which is an average of 8.8 accidents per day, including 104 emergency situations, or 3.25 % of the total amount, were associated with hidden water leaks. The actual specific emergency rate of the Lviv water supply network in 2020 was 1.41 accidents per 1 km.

According to various expert estimations, the share of water losses through hidden leaks is in the range of 50–90 % of the total losses due to leaks (Puust, 2010; Beuken, 2008). Therefore, the small share of accidents related to hidden leaks recorded in Lviv in 2020 (only 3.25 %) is most likely not representative for the assessment of the ratio of hidden and open leaks, but only indicates the presence, but currently quite low the effectiveness of the system of monitoring and early detection of leaks on the Lviv water supply system.

A method of simulating the simultaneous multi-leakage

Since the presence of an open or hidden water leak in a section of the water supply network is the main and predominant cause of accidents, further on in this work, the emergency of the site is equated with the presence of a water leak, and by multiple accidents we mean multiple leaks, that is, the simultaneous presence of two or more leaks at the same section during a certain period of time. An analytical method based on the Poisson distribution, which is the distribution of a discrete random variable that is equal to the number of events that occurred in a certain fixed time, provided that such events occur with a certain known average intensity and independently from each other (Kartashov, 2008). According to the Poisson distribution, the probability of occurrence of exactly k leaks in a certain period of time T is defined as:

$$p(k) = \frac{(\mu)^k}{k!} exp(-\mu), \tag{1}$$

where μ is the mathematical expectation of the number of leaks for the period T.

This study assumes that the sequence of leaks from the water supply network satisfies the conditions of stationarity, absence of consequences, and ordinariness. By stationarity we mean that the average frequency of formation of new leaks is constant and does not depend on the time of year, day of the week, hour of the day or other time frames. The absence of consequences means that the probability of the appearance of new leaks at the control site does not depend on the history of this site, that is, on the number of emergency leaks in any previous time interval. Ordinariness means that it is practically impossible for two or more sources to appear simultaneously in a sufficiently short period of time. Strictly speaking, the no-consequence condition neglects the effect of crash site regression, assuming that for a fixed forecast period in the future the average crash frequency will be the same as well as for the available previous observation period. The principle of ordinariness for leaks in pressure water supply networks can be violated due to short-term extreme transient processes that affect the entire control section, for example, when a hydraulic shock occurs in the network.

Results and discussion

Ranges and trends of changes in the specific emergency rate of water supply networks in Ukraine in 2007−2020

A statistical analysis of the distribution of the specific emergency rate of water supply networks in the regions of Ukraine in 2020 indicates the presence of a particularly large spread of values, which significantly exceeds the standard deviation of the sample as a whole (Fig. 2). The average specific emergency rate of water supply networks was determined as the length-weighted average, taking into account the actual total length of networks by region:

$$SE_{an.mid} = \frac{\Sigma SE_{an.i} L_i}{\Sigma L_i}, \qquad (2)$$

where $SE_{an.i}$ is the specific annual emergency rate of networks in the i-th region, $km^{-1}yr^{-1}$; L_i is the total length of water supply networks in the i-th region, km.

The length-weighted average value of the specific emergency rate of water supply networks in Ukraine in 2020, taking into account all reported data, is $SE_{an.mid.1}$= 5.87 $km^{-1}yr^{-1}$. This is in 1.95 times exceeds the simple arithmetic average of indicators in the regions of 3.01 km^{-1} $year^{-1}$ and in 1.89 times more than the basic value of the specific emergency rate $SE_{an.mid.0}$ = 3.1 $km^{-1}yr^{-1}$, adopted in the Water Strategy of Ukraine for the period until 2050 for the reference point, which is planned to decrease by 3 % every year (Vodna Stratehiia Ukrainy, 2022).

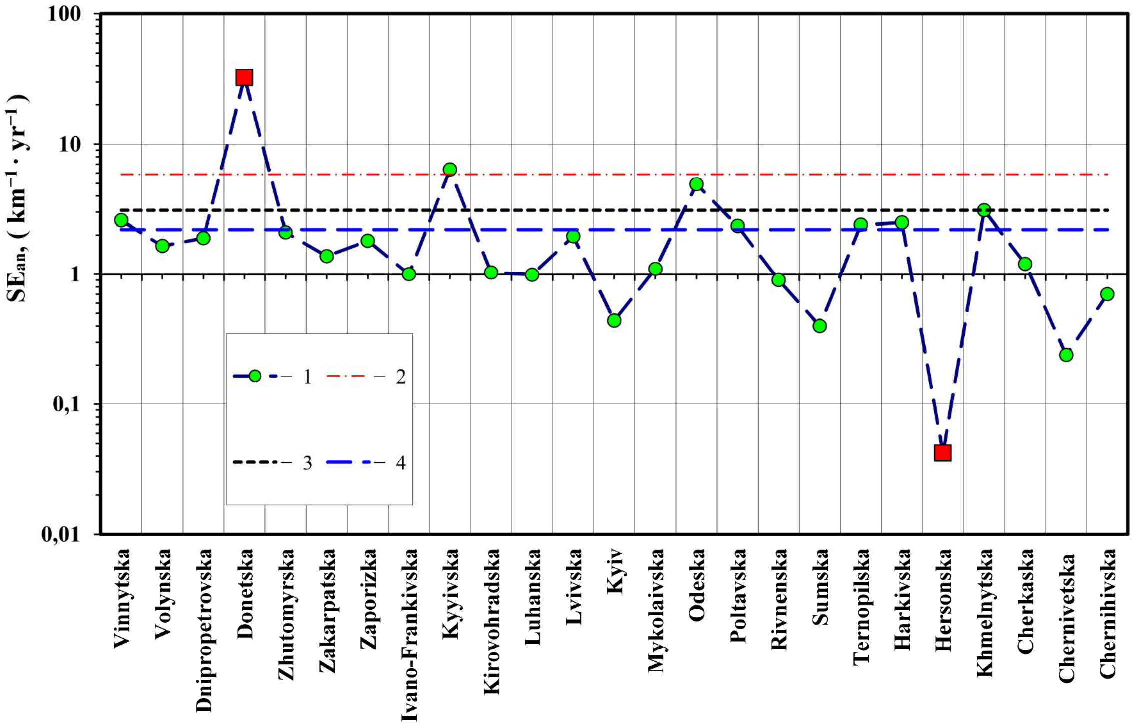


Fig. 2. Specific annual emergency rate of water supply networks by regions of Ukraine in 2020: 1 − official data (National Report, 2021); 2 − weighted average $SE_{an.mid.1}$ = 5.87 $km^{-1}yr^{-1}$; 3 − $SE_{an.mid.0}$ = 3.1 $km^{-1}yr^{-1}$ (Vodna Stratehiia Ukrainy, 2022); 4 − weighted average $SE_{an.mid.2}$ = 2.12 $km^{-1}yr^{-1}$

Deviations from the average values of individual sample values cannot be justified in any way. Under similar technical and economic conditions, which include the degree of amortization of water supply networks, the cost of selling 1 m^3 of water, etc., the specific emergency rate in the Donetsk region in 2020 (32.26 $km^{-1}yr^{-1}$) in 5.5 times exceeded the average value for the country, while for the Kherson region this indicator was 0.042 $km^{-1}yr^{-1}$ or in 139.8 times less than the average one. The ratio of the official water supply specific emergency rates in Donetsk and Kherson regions in 2020 was equal to 768, which clearly casts doubt on the objectivity of respective data.

Based on the above analysis, the extreme maximum and minimum values of the specific emergency rate of water supply networks in 2020 (respectively, 32.26 km^{-1}yr^{-1} for the Donetsk region and 0.042 km^{-1}yr^{-1} for the Kherson region) were removed from the following statistical treatments as clearly out-of-sample and highly likely to be erroneous. Given the large length of networks in the Donetsk region in 2020 (15.38 thous. km or 12.6 % of the total length of water supply networks in Ukraine), the average value of the specific emergency rate in the refined reduced sample decreases to $SE_{an.mid.2}$= 2.21 km^{-1}yr^{-1} (Fig. 2).

Statistical analysis also indicates a very low degree of correlation between the specific emergency rate and the share of emergency water supply networks by regions in 2020 (Fig. 3). The correlation coefficient is 0.400, which is significantly below the minimum threshold value of 0.7, at which it is already possible to conclude that there is a correlation between the initial parameters.

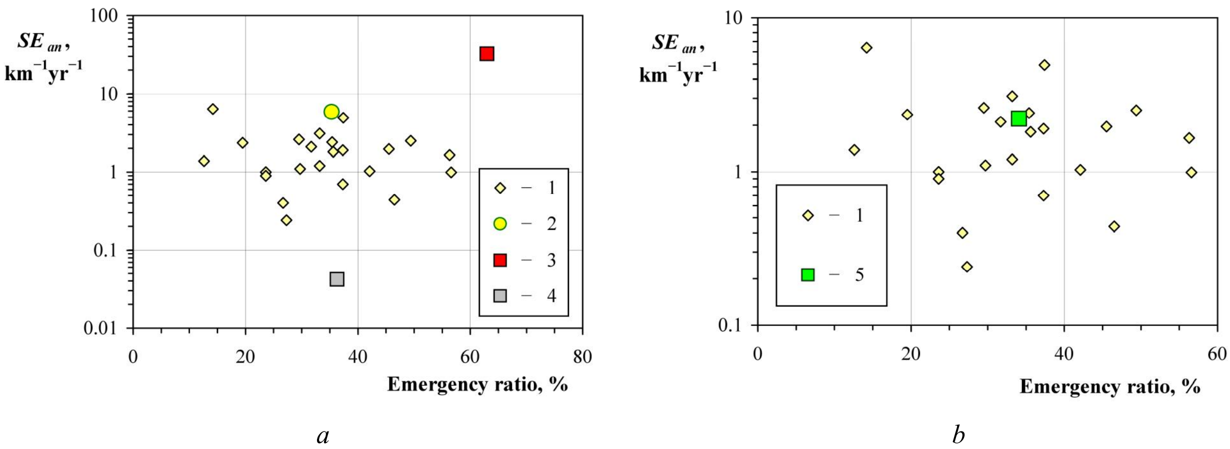


Fig. 3. Correlation between the specific emergency rate of water supply networks in the regions of Ukraine in 2020 and the corresponding shares of emergency networks: a – all actual data; b – without abnormal values; 1 – official data (National Report, 2021); 2 – average weighted index (R_E= 35.34 %; $SE_{an.mid.1}$= 5.87 km^{-1}yr^{-1}); 3, 4 – data for Donetsk and Kherson regions respectively; 5 – weighted average without abnormal values (R_E = 34.1 %; $SE_{an.mid.2}$ = 2.21 km^{-1}yr^{-1})

Results of modelling the probability of multiple accidents of water supply networks.

Based on the principle of stationarity of emergency leaks on water supply networks adopted above, the mathematical expectation of the number of leaks on a network section of length L for an arbitrary time period T:

$$\mu_T = SE_{an} \cdot L \cdot T / 365, \tag{3}$$

where SE_{an} is the annual specific emergency rate of the section, km^{-1}yr^{-1}; L − length of the section of the water supply network, km; T − time period, days.

Table 1 summarizes the annual probabilities of the occurrence of various number of leakage accidents on a section of the water supply network 1 km long for different typical values of the specific annual accident rate in the range of SE_{an} = 0.1–5 km^{-1}yr^{-1}. Let's introduce next notations: p_p is the probability of one or more emergency leaks in the section of the water supply network; p_{2+} is the probability of multiple leakages (occurrence of two or more simultaneous emergency leaks) in a section of the water supply network. The maximum probabilities at $SE_{an} \geq N_L$ correspond to the annual number of leakage accidents N_L and (N_L – 1), with decreasing probability in both directions (Table 1). The annual probability of multi-leakage p_{2+} increases sharply with growing of SE_{an} index, reaching a value of 0.648 based on the actual average annual emergency rate of water supply networks in Ukraine of 2.21 km^{-1}yr^{-1} as of

2020. So, at each randomly selected kilometer of water supply networks of Ukraine, with an average probability of 64.8 %, 2 or more leaks occur during a calendar year. The maximum acceptable multi-failure probability of 0.02 from a practical point of view corresponds to the specific annual failure rate of networks of 0.215 $km^{-1}yr^{-1}$, which corresponds to networks in practically perfect technical condition. The obtained results indicate the need for water supply enterprises to follow an active policy of monitoring networks for the presence of leaks in order to prevent large losses of water and deterioration of the network condition. A passive policy leads both to an increase in water loss and deterioration of networks, and to a sharp complication of the task of detecting new hidden leaks even for new, previously accident-free sections of water networks.

Table 1

Probabilities of different number of leakage accidents per 1 km of water supply network per year

Number of leakages, N_L	Annual probabilities based on SE_{an}, $km^{-1}yr^{-1}$:							
	5	4	3	2	1	0.5	0.2	0.1
0	0.0067	0.0183	0.0498	0.1353	0.3679	0.6065	0.8187	0.9048
1	0.0337	0.0733	0.1494	0.2707	0.3679	0.3033	0.1637	0.0905
2	0.0842	0.1465	0.224	0.2707	0.1839	0.0758	0.0164	0.0045
3	0.1404	0.1954	0.224	0.1804	0.0613	0.0126	0.0011	0.0002
4	0.1755	0.1954	0.168	0.0902	0.0153	0.0016	5E-05	4E-06
5	0.1755	0.1563	0.1008	0.0361	0.0031	0.0002	2E-06	8E-08
6	0.1462	0.1042	0.0504	0.012	0.0005	1E-05	7E-08	1E-09
7	0.1044	0.0595	0.0216	0.0034	7E-05	9E-07	2E-09	2E-11
8	0.0653	0.0298	0.0081	0.0009	9E-06	6E-08	5E-11	2E-13
9	0.0363	0.0132	0.0027	0.0002	1E-06	3E-09	1E-12	2E-15
10	0.0181	0.0053	0.0008	4E-05	1E-07	2E-10	2E-14	2E-17
10+	0.0137	0.00284	0.0003	8E-06	1E-08	8E-12	4E-16	0
p_p	0.9933	0.98168	0.9502	0.8647	0.6321	0.3935	0.1813	0.0952
p_{2+}	0.9596	0.9084	0.8009	0.5940	0.2642	0.0902	0.0175	0.0047

If the hypothesis of stationarity is fulfilled, the number of calculated leaks on the site is directly proportional to the time period. This confirms the importance of quick localization of leaks and their elimination to reduce the probability of multiple accidents in the area, which itself already complicates the task of localization, and therefore network repair. Given that the duration of detection, localization and elimination of leaks depends on many partial parameters, a special parameter is used − the duration of the localization and repair period (LRP) T_{LRP}, which means the period in days from the appearance of a hidden leak on the site to its elimination. Therefore, the mathematical expectation of the number of leaks on the network section of length L during the LRP:

$$\mu_{LRP} = SE_{an} \cdot L \cdot T_{LRP} / 365 . \quad (4)$$

Thus, the probability of an arbitrary number of leaks, and therefore the probability of multi-leakage at an arbitrary section of the water supply network, depends on one dimensionless complex, the average accident rate of the section during the LRP μ_{LRP}:

$$p(k) = \frac{\mu_{LRP}^{k}}{k!} exp(-\mu_{LRP}) . \quad (5)$$

Eq. (5) has an analytical solution with respect to the probability of two or more simultaneous accidents-leaks during the LRP:

$$p_{2+} = 1 - (1 + \mu_{LRP})\exp(-\mu_{LRP})\,. \tag{6}$$

The graphic interpretation of Eq. (6), shown in Fig. 4, indicates the high reliability of the dependence of the probability p_{2+} on mathematical expectation μ_{LRP} by the simple power dependence with coefficient of determination R^2= 0.9998:

$$p_{2+} = 0.406\mu_{LRP}^{1.968}\,. \tag{7}$$

In the expanded form, Eq. (5) can be written as:

$$p(k) = \frac{(SE_{an} \cdot L \cdot T_{LRP} / 365)^k}{k!}\exp(-SE_{an} \cdot L \cdot T_{LRP} / 365)\,, \tag{8}$$

thus, under the condition of fulfilling the hypotheses of stationarity, absence of consequences and ordinariness, the probability of the occurrence of multiple leaks in an arbitrary section of the water supply network is a function of the specific annual emergency rate, the length of the section and the LRP duration.

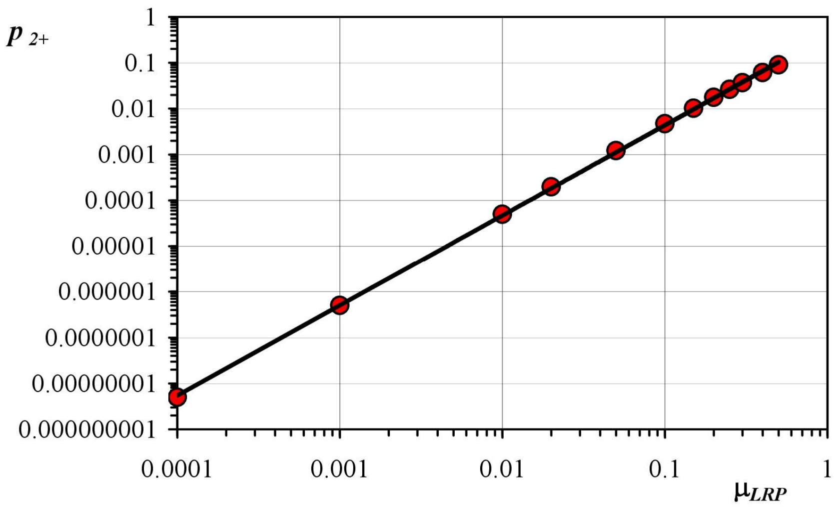


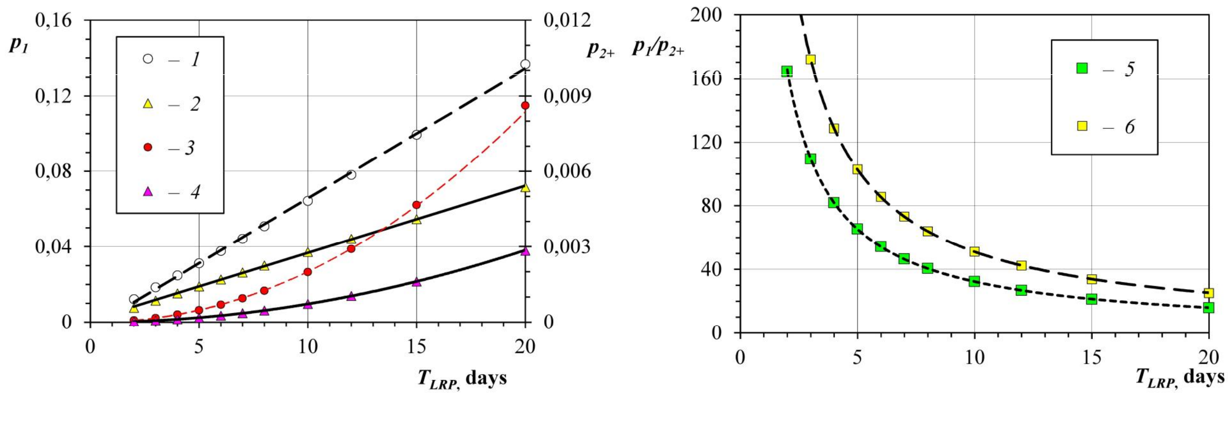
Fig. 4. The probability p_{2+} of multi-leakage during LRP depending on the mathematical expectation μ_{LRP}

The duration of LRP is an important operational parameter that directly affects the probability of multiple accidents. In the Table 2 given probabilities the occurrence of one or more leaks on a section of the pressure water supply network 1 km long for typical values of the duration of the localization and repair period T_{LRP} = 2−20 days for four characteristic values of the specific annual accident rate SE_{an}, in particular: on the Lviv water pipeline (1.41 $km^{-1}yr^{-1}$), in Ukraine as a whole as of 2020 for all regions (5.87 $km^{-1}yr^{-1}$) and without taking into account anomalous data (2.21 $km^{-1}yr^{-1}$), as well as for the base value of the specific annual accident rate according to the Water Strategy of Ukraine for the period until 2050 (3.1 $km^{-1}yr^{-1}$). The probability p_1 of the occurrence of a single leak in the indicated range of the specific annual emergency rate is almost a linear function of the LRP duration (Fig. 5, *a*), while the probability of multiple accidents p_{2+} is proportional to the duration of the LRP only when the T_{LRP} < 5−6 days, followed by a more intensive growth. For the average specific annual emergency rate in Ukraine SE_{an} = 2.21 $km^{-1}yr^{-1}$ and for the LRP duration of 5 days, the probability of multi-accident p_{2+} is only 1.5 % of the probability of the occurrence of one leak p_1, while with the duration of LRP 20 days – already 6.3 %. For the average specific annual accident rate of the Lviv water pipeline SE_{an}= 1.41 $km^{-1}yr^{-1}$ corresponding shares are proportionally lower, namely 1.0 % at T_{LRP} = 5 days and 4.0 % at T_{LRP} = 20 days (Fig. 5, *b*).

Table 2

Probabilities of the simultaneous occurrence of one or more leaks in the section of the water network with a length of L = 1 km depending on the duration of the LRP at the characteristic values of the specific annual emergency rates SE_{an}

T_{LRP}, days	Probabilities p_1 and p_{2+} for different SE_{an}, km^{-1}yr^{-1}							
	1.41		2.21		3.1		5.87	
	p_1	p_{2+}	p_1	p_{2+}	p_1	p_{2+}	p_1	p_{2+}
2	7.67E-03	2.97E-05	1.20E-02	7.27E-05	1.67E-02	1.43E-04	3.11E-02	5.06E-04
3	1.15E-02	6.66E-05	1.78E-02	1.63E-04	2.48E-02	3.19E-04	4.60E-02	1.13E-03
4	1.52E-02	1.18E-04	2.36E-02	2.89E-04	3.28E-02	5.64E-04	6.03E-02	1.98E-03
5	1.89E-02	1.84E-04	2.94E-02	4.49E-04	4.07E-02	8.77E-04	7.42E-02	3.06E-03
6	2.26E-02	2.64E-04	3.50E-02	6.44E-04	4.84E-02	1.26E-03	8.76E-02	4.37E-03
7	2.63E-02	3.59E-04	4.06E-02	8.73E-04	5.60E-02	1.70E-03	1.01E-01	5.88E-03
8	3.00E-02	4.68E-04	4.61E-02	1.14E-03	6.35E-02	2.21E-03	1.13E-01	7.60E-03
10	3.72E-02	7.27E-04	5.70E-02	1.76E-03	7.80E-02	3.41E-03	1.37E-01	1.16E-02
12	4.43E-02	1.04E-03	6.76E-02	2.52E-03	9.20E-02	4.85E-03	1.59E-01	1.64E-02
15	5.47E-02	1.62E-03	8.29E-02	3.88E-03	1.12E-01	7.46E-03	1.90E-01	2.48E-02
20	7.15E-02	2.84E-03	1.07E-01	6.77E-03	1.43E-01	1.29E-02	2.33E-01	4.19E-02



a *b*

Fig. 5. Probability indicators of multiple leaks per 1 km of water supply networks depending on the duration of the LRP: a – the probability of leaks p_1 (1, 2) and p_{2+} (3, 4); b – ratio p_1/p_{2+}; for SE_{an}=2.21 km^{-1}yr^{-1} (1, 3, 5); for SE_{an}=1.41 km^{-1}yr^{-1} (2, 4, 6)

It should be noted that the specific annual accident rate of the site, as well as its length, are sufficiently defined parameters, while the duration of the LRP for the same site, in the presence of the same leak detection system, can differ significantly. It depends largely on the type of leak, which is a complex function of age, material, pipe wall thickness, hydrogeological conditions, etc. Thus, the probability of multiple accidents of any section of the water supply network must be expressed as a function of the annual accident rate of this section E_{an} and the T_{LRP} period:

$$p_{2+} = 1 - (1 + E_{an} \cdot T_{LRP}) exp(-E_{an} \cdot T_{LRP}) \quad (9)$$

In general, depending on the specific failure rate and the length of the section, the annual failure rate of sections of water supply networks varies within wide limits E_{an} = 0.1–10 yr^{-1}. The results of modelling the dependence of the multi-accident probability for typical values of the annual emergency E_{an} in the range from 0.1 yr^{-1} to 10 yr^{-1} are presented in Fig. 6.

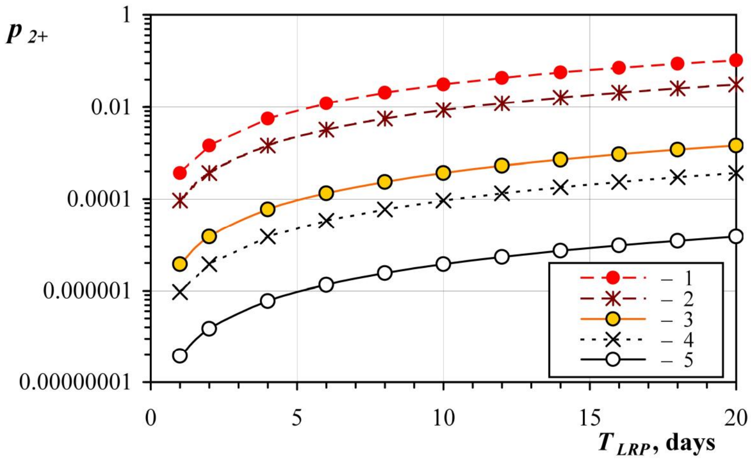


Fig. 6. Probability of multi-leakage of sections of water supply networks depending on the LRP duration for different values of annual emergency rate E_{an}: 1 – 0.1 yr^{-1}; 2 – 0.5 yr^{-1}; 3 – 1 yr^{-1}; 4 – 2 yr^{-1}; 5 – 5 yr^{-1}; 6 – 10 yr^{-1}

The maximum permissible (limiting) duration of the LRP significantly shortened both with increasing the annual emergency rate of the section and by reducing the probability of multi-leakage p_{2+} (Fig. 7). For example, to ensure the absence of multi-leakage at 99 %, which corresponds to the probability p_{2+} = 0.01, at the value of the site's annual emergency rate $E_{an} \geq 5.87$ yr^{-1} the duration of LRP should not exceed 9 days.

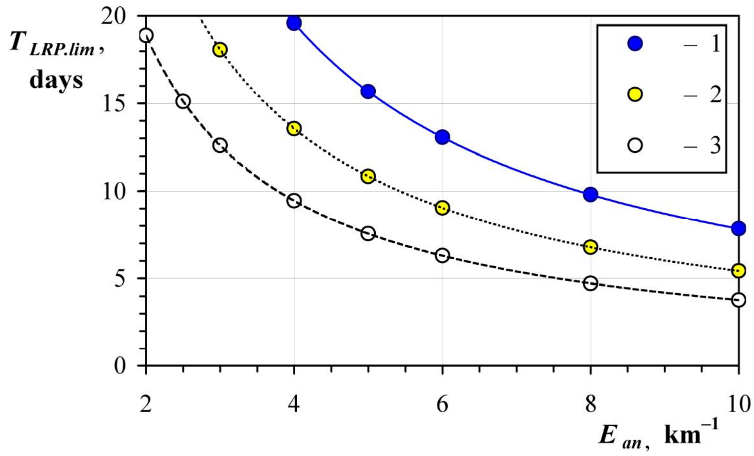


Fig. 7. The maximum permissible durations of LRP as a function of the annual emergency for typical multi-leakage probabilities p_{2+}: 1 – 0.02; 2 – 0.01; 3 – 0.005

Approximations of results obtained for characteristic multi-leakage probabilities 0.005; 0.01 and 0.02, shown in Fig. 7, indicate that the limit time of the LRP is inversely proportional to the annual emergency rate of the section E_{an}:

$$T_{LRP.lim} = K / E_{an}, \tag{10}$$

where the coefficient K depends on the multi-leakage probability (Fig. 8):

$$K = 600 p_{2+}^{0.52} . \tag{11}$$

Thus, the limit duration of LRP, which corresponds to practically important values of the probability of multi-accident p_{2+} = 0.1−3.0 % for sites with a typical annual emergency rates E_{an}= 1−10 yr^{-1} can be evaluated by a semi-empirical power dependence:

$$T_{LRP.lim} = 600 p_{2+}^{0.52} / E_{an} . \tag{12}$$

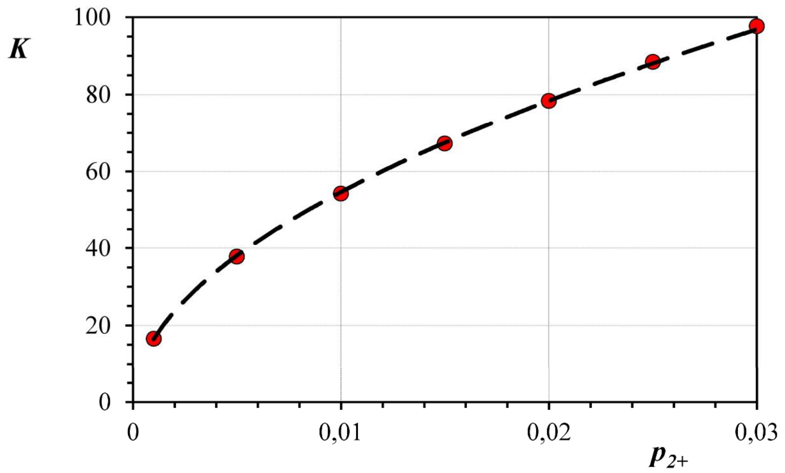


Fig. 8. Dependence of the coefficient K in Eq. (10) on the multi-leakage probability

It should be noted that the model of multi-leakage of water supply networks presented above is developed on the basis of the Poisson distribution law of independent events, subject to the fulfilment of three partial hypotheses: stationarity, absence of consequences, and ordinariness. The specified hypotheses can be verified and reliably quantified only on the basis of long-term field observations of respective sites of the water supply networks.

Conclusions

Water losses due to water leaks from water supply networks are one of the main factors that directly affect the technical and economic efficiency of water supply systems as a whole. According to the available results of full-scale field studies in different countries of the world, hidden water leakages from water supply networks account for 50 % to 90 % of the total water losses due to leaks. The presence of two or more simultaneous leaks in a section of the water supply network significantly reduces the accuracy of localization of hidden leaks, which makes the assessment of the multi-leakage probability as very important task.

According to official reports, an analysis of the state of water supply networks in Ukraine and Lviv is carried out, it is found that as of the end of 2020, the specific annual emergency rate was 2.21 km^{-1}yr^{-1} for Ukraine as a whole and 1.41 km^{-1}yr^{-1} for Lviv water supply network. At the same time, the very low correlation between the share of emergency networks and the specific annual emergency rate in the regions of Ukraine indicates the subjectivity of individual reported data. Based on this fact and the variability of the specific emergency rate on each specific water supply network depending on the age and material of the pipes, it is recommended, when estimating probabilities, to proceed not from averaged values, but from statistical parameters for the relevant site of the water supply network.

Presented probabilistic model of the multi-emergency problem of water supply networks is based on the method of independent events (Poisson distribution), provided that the hypotheses of stationarity, absence of consequences and ordinariness of emergency leaks are fulfilled. The analytical dependence (6) of the multi-leakage probability on the specific annual emergency rate of the site, its length and the LRP duration is obtained. Numerical values of the probability of multi-leakage are analyzed, based on the average in Ukraine and the average in Lviv specific annual emergency rates of water supply networks. A generalized semi-empirical dependence (12) is obtained for the estimation of the maximum permissible duration of the LRP as a function of annual emergency rate of the site for the given multi-leakage probability.

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ЙМОВІРНОСТІ ОДНОЧАСНОЇ БАГАТОАВАРІЙНОСТІ НА ДІЛЯНКАХ ВОДОПРОВІДНИХ МЕРЕЖ У ПРОЦЕСІ ЛОКАЛІЗАЦІЇ ПРИХОВАНИХ ВИТОКІВ ВОДИ

Приховані витоки з водопровідних мереж за різними оцінками складають від 50 % до 90 % від загальних втрат на витоки. Наявність на ділянці водопровідної мережі двох та більше одночасних витоків суттєво знижує точність локалізації прихованих витоків, що робить актуальною задачу щодо оцінки ймовірностей багатоаварійності ділянок залежно від їх попередніх статистичних параметрів аварійності. Для імовірнісного опису проблеми багатоаварійності водопровідних мереж застосовано метод незалежних подій Пуассона за умови виконання гіпотез стаціонарності, відсутності наслідків та ординарності аварійних витоків. За результатами аналізу офіційних статистичних даних отримано, що у 2020 р. середня питома річна аварійність водопровідних мереж загалом в Україні становила 2,21 $км^{-1}рік^{-1}$, а для Львівського водопроводу − 1,41 $км^{-1}рік^{-1}$. Низька кореляція між часткою аварійних мереж та питомою річною аварійністю по областях України вказує на суб'єктивність окремих звітних даних. Виходячи з цього факту та з варіативності питомої аварійності на кожній конкретній водопровідній мережі, залежно від віку та матеріалу труб, рекомендовано виходити не з осереднених значень, а зі статистичних параметрів для відповідної дільниці водопровідної мережі. Отримано аналітичну залежність ймовірності багатоаварійності від питомої річної аварійності ділянки, її довжини та тривалості локалізаційно-ремонтного періоду. Проаналізовано чисельні значення ймовірності багатоаварійності, виходячи з середньої питомої річної аварійності водопровідних мереж в Україні та у Львові. Отримано узагальнену напівемпіричну залежність для визначення максимальної гранично допустимої тривалості локалізаційно-ремонтного періоду від річної аварійності ділянки для забезпечення неперевищення заданої ймовірності багатоаварійності.

Ключові слова: ймовірність багатоаварійності, локалізаційно-ремонтний період, одночасність витоків, питома річна аварійність, приховані витоки, розподіл Пуассона.